Cold quark matter and neutron stars

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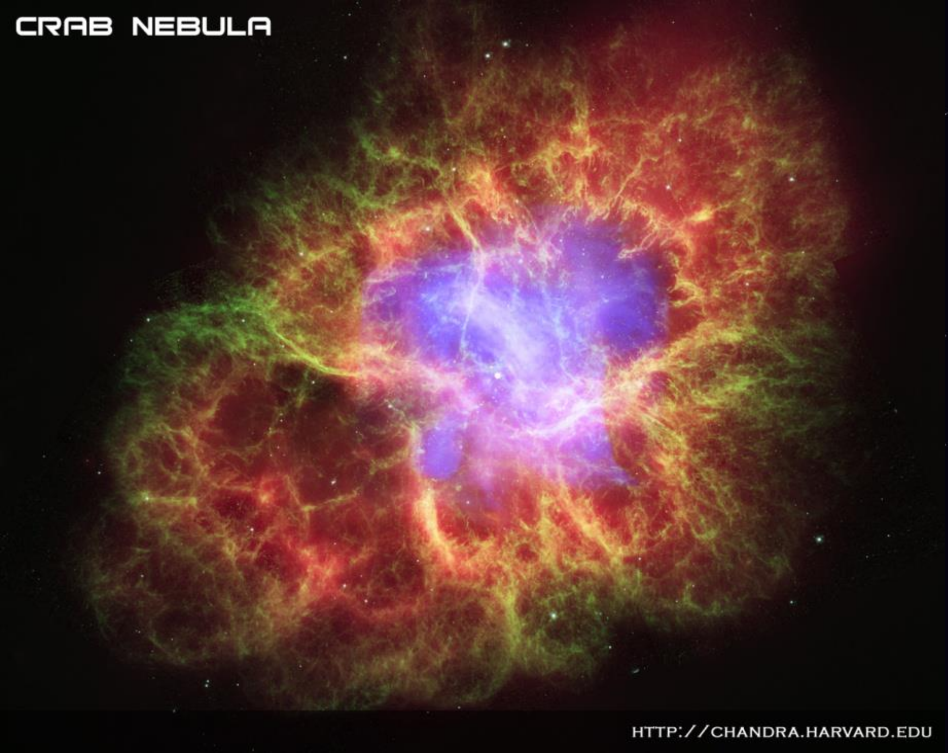
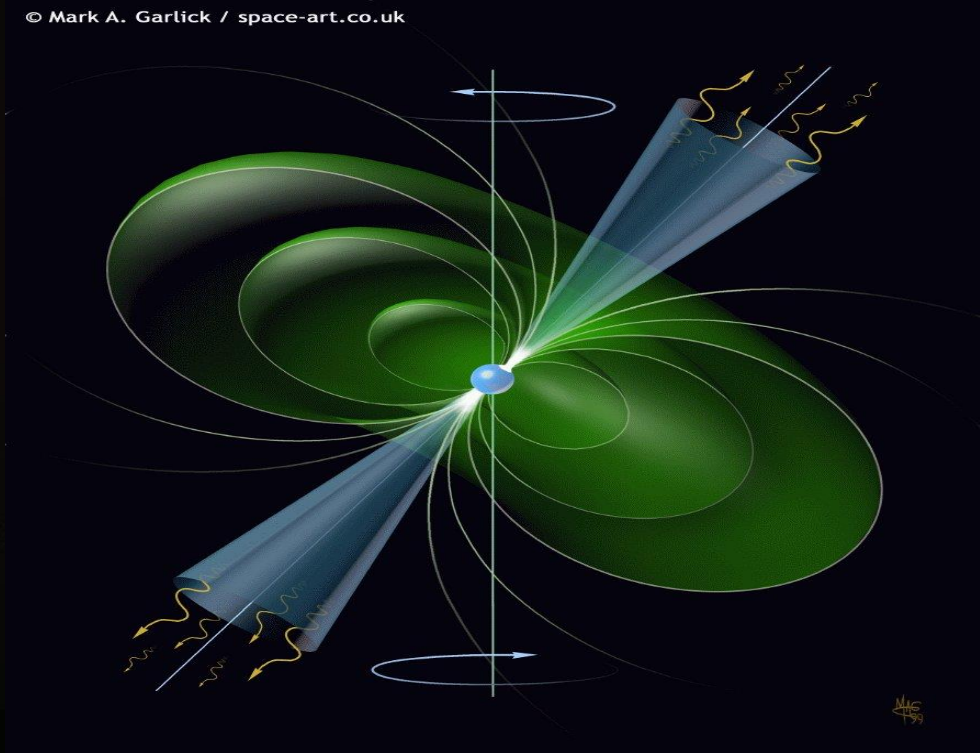
University of Helsinki

QCD at Finite Temperature and Heavy-Ion Collisions,

BNL, 13.2.2017

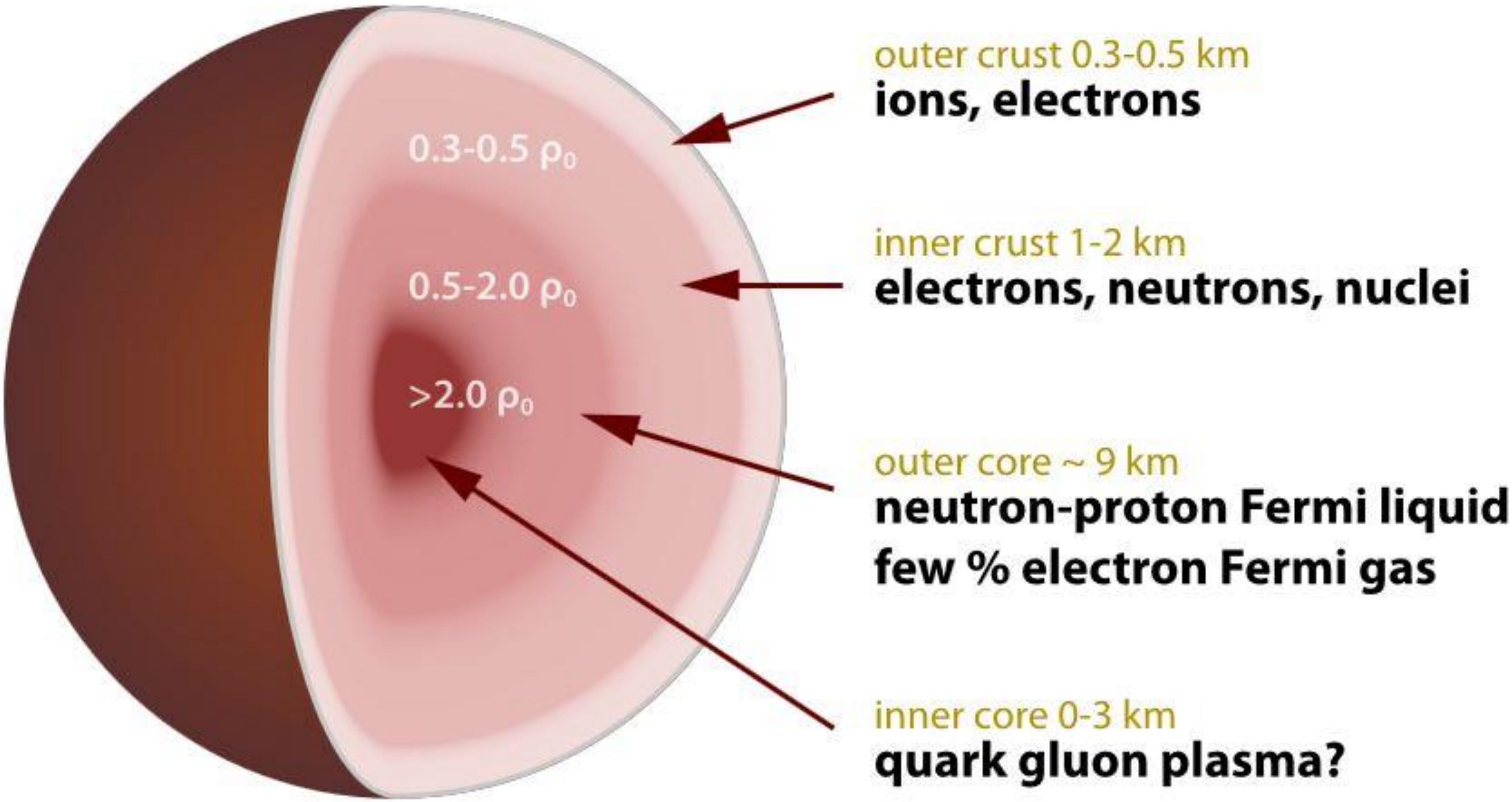
A. Kurkela, AV, PRL 117, 042501 (2016)
C. Hoyos, N. Jokela, D. Rodriquez, AV, PRL 117, 032501 (2016); PRD 94, 106008 (2016)



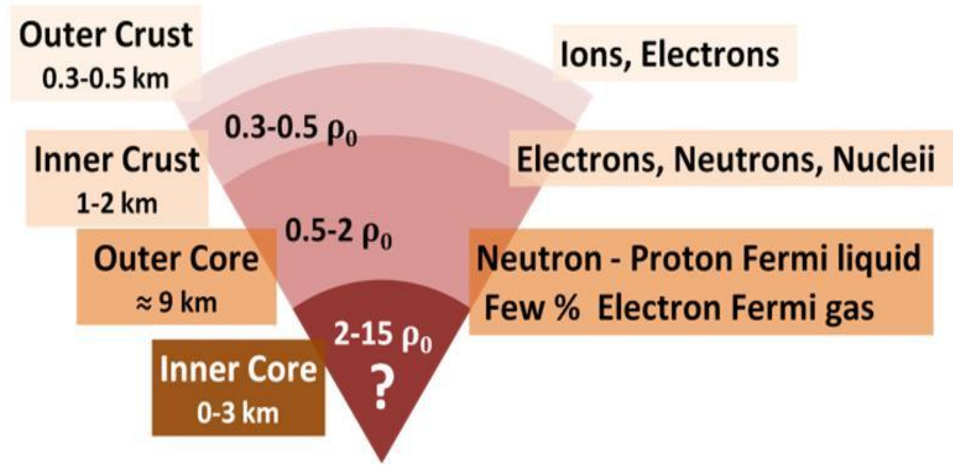


When a hydrogen burning star runs out of fuel:

- $M \lesssim 9M_{\rm sun} \Rightarrow$ White dwarf
- $M \gtrsim 9M_{\rm sun} \Rightarrow$ Supernova explosion
  - $M \gtrsim 20M_{\rm sun} \Rightarrow$ Gravitational collapse into BH
  - $M \lesssim 20M_{\rm sun} \Rightarrow$ Gravitational collapse into…

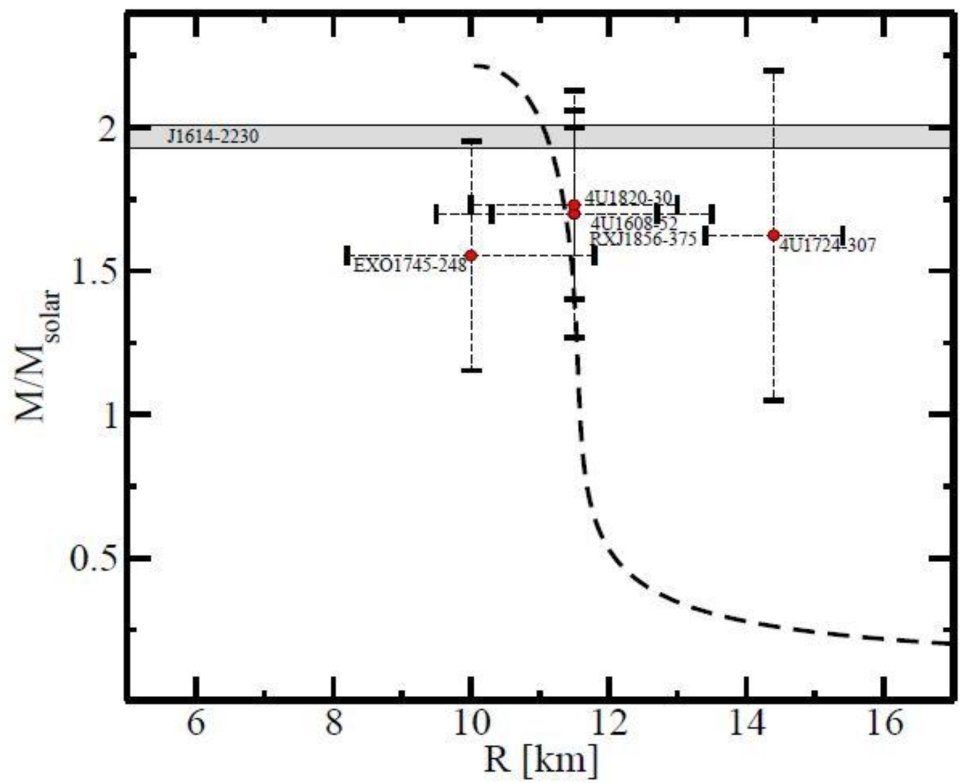

0.3-0.5 ρ_0
0.5-2.0 ρ_0
>2.0 ρ_0
outer crust 0.3-0.5 km
ions, electrons
inner crust 1-2 km
electrons, neutrons, nuclei
outer core ~ 9 km
neutron-proton Fermi liquid
few % electron Fermi gas
inner core 0-3 km
quark gluon plasma?

Classic problem in nuclear astrophysics: predict composition and main properties of neutron stars



Characteristics:

- Masses $\lesssim 2M_{\text{sun}}$
- Radii $10 - 15\text{km}$
- Spin frequencies $\lesssim \text{kHz}$
- Temperature $\lesssim \text{keV}$



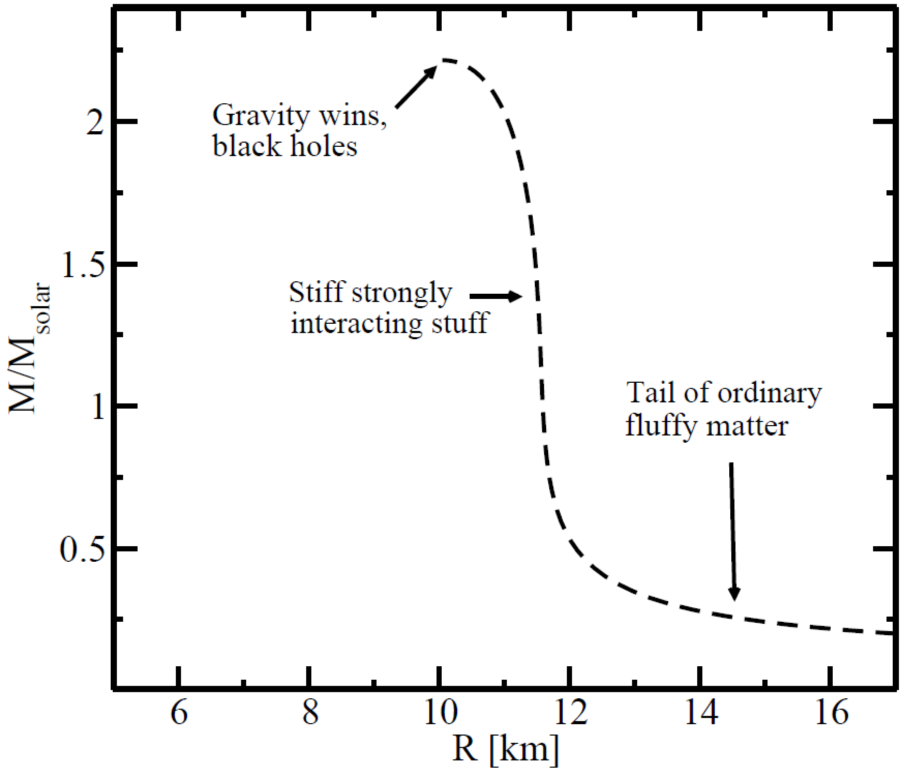
$$\frac{dM(r)}{dr} = 4\pi r^2 \varepsilon(r),$$
$$\frac{dp(r)}{dr} = -\frac{G\varepsilon(r)M(r)}{r^2}\frac{(1+p(r)/\varepsilon(r))\left(1+4\pi r^3 p(r)/M(r)\right)}{1-2GM(r)/r}$$

$$\varepsilon(p) \Rightarrow M(R)$$

Theory challenge: find EoS of nuclear/quark matter that is

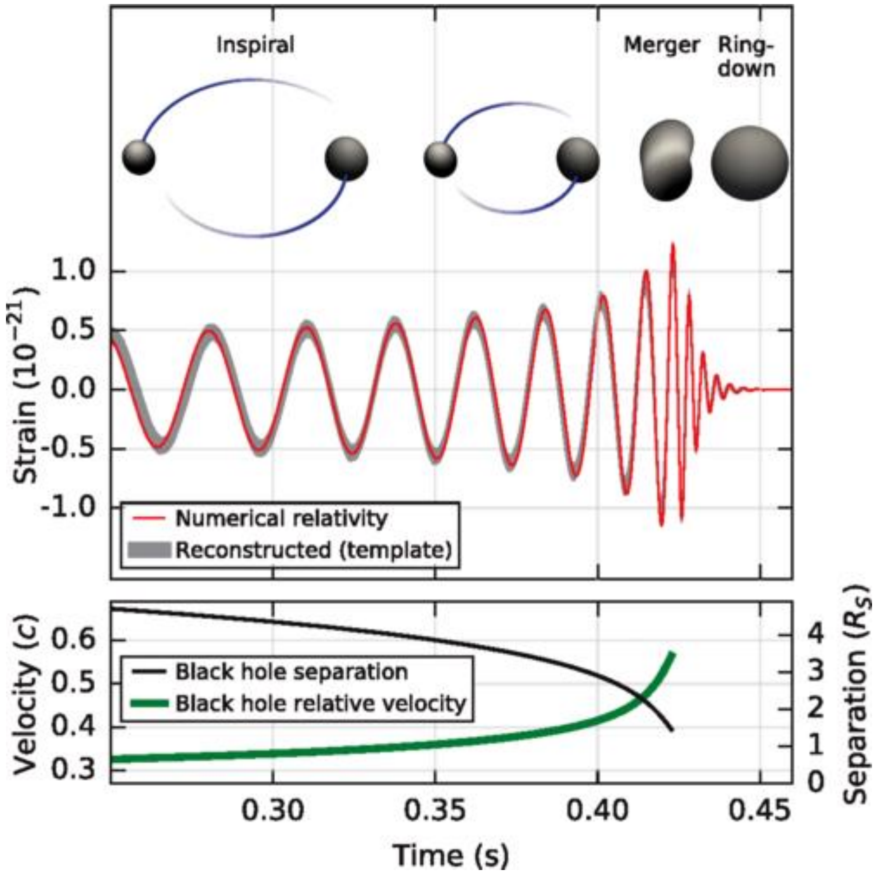
- Cold: $T \approx 0$
- Electrically neutral:
  $$2/3n_u - n_d/3 - n_s/3 + n_e = 0$$
- In beta equilibrium:
  $$\mu_B/3 = \mu_d = \mu_s = \mu_u + \mu_e$$

and compare to observations.

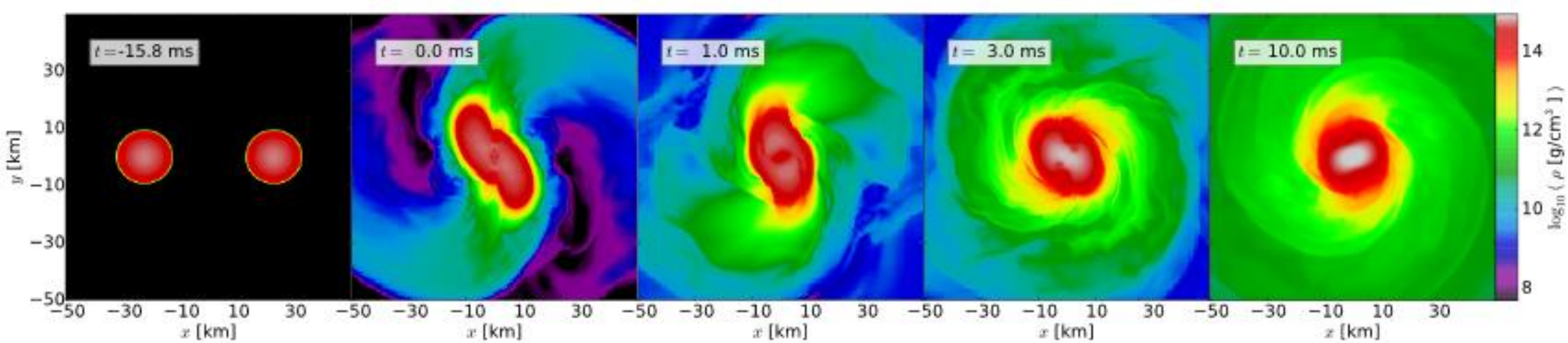


Ultimate question: *is there quark matter inside the stars?*

Breakthrough in gravitational wave detection: LIGO observation of BH merger >1 billion light years away



Outstanding opportunities for neutron star physics from NS mergers – NSs becoming truly a QCD laboratory!



I. Neutron star Equation of State: Status and challenges
II. New developments I: Accounting for thermal effects in pQCD
III. New developments II: Hints from holography
IV. Final thoughts

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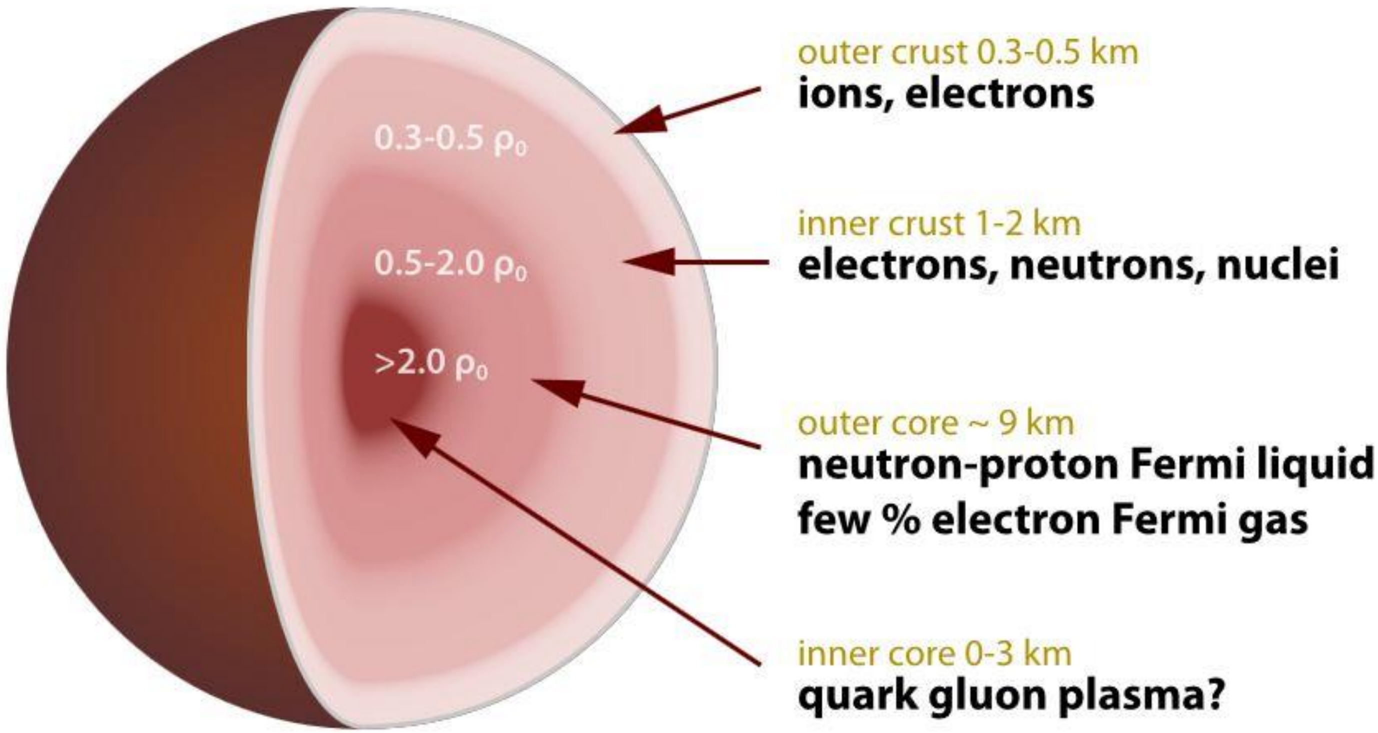
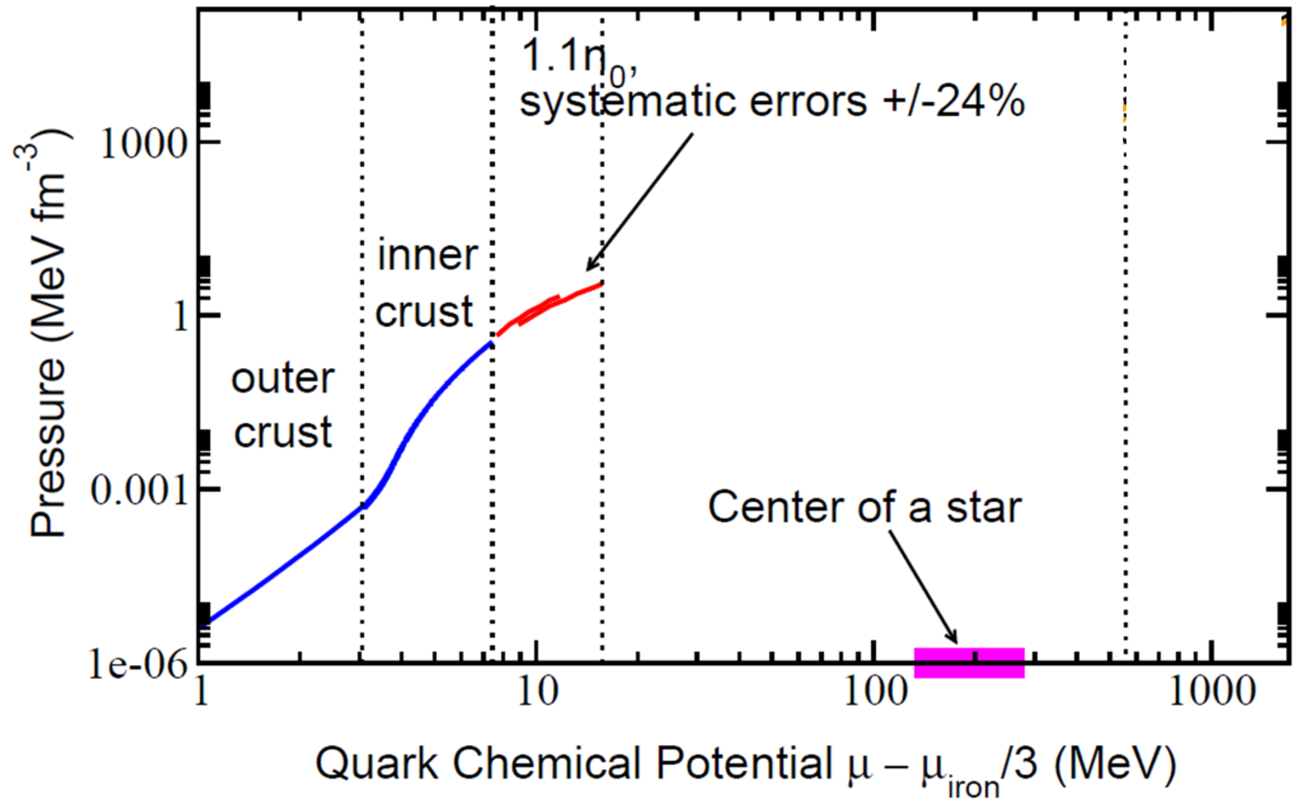


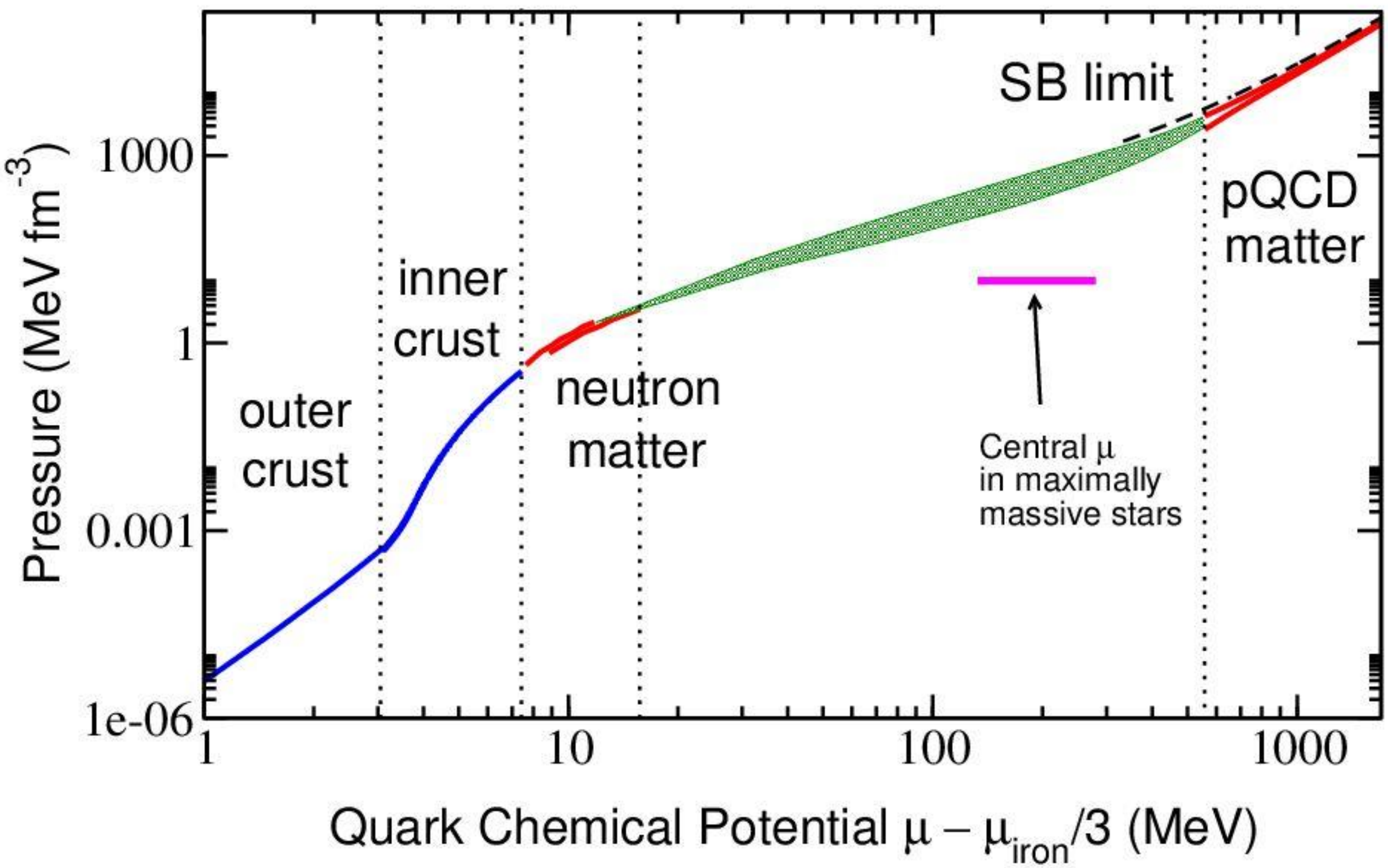
Proceeding inwards from the crust:

- μ_B increases gradually, starting from μ_{Fe}
- Baryon and mass density increase beyond $n_s \equiv \rho_0 \approx 0.16/\mathrm{fm}^3 \approx 2 \times 10^{14}\mathrm{g/cm}^3$
- Composition changes from nuclei to neutron matter



Traditional nuclear physics methods work at low density, but to reach saturation density, need Chiral Effective Theory

- At $1.1n_{\mathrm{s}}$, current errors $\pm 24\%$ - mostly due to uncertainties in effective theory parameters
- State-of-the-art NNNLO Tews et al., PRL 110 (2013), Hebeler et al., APJ 772 (2013)

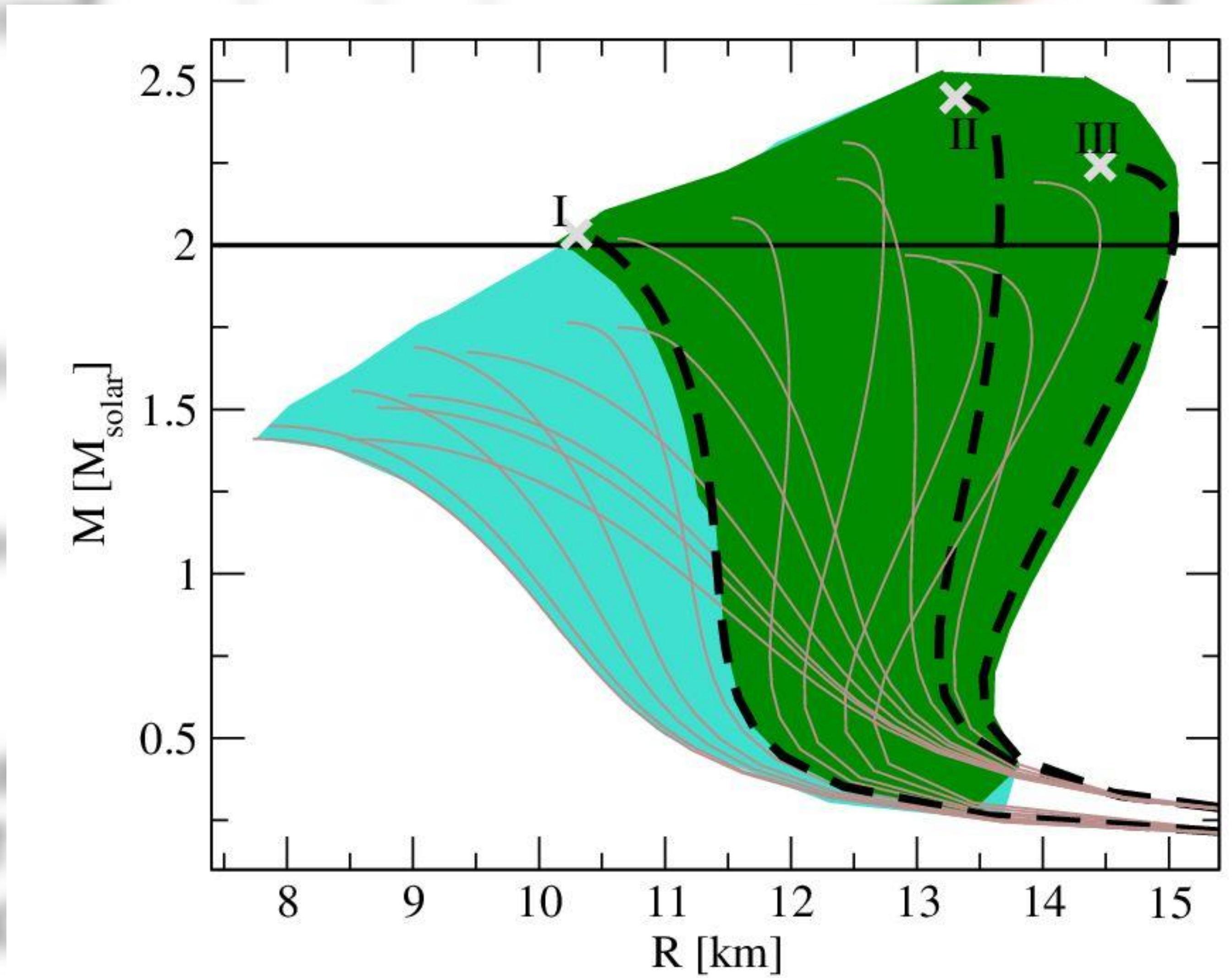


Kurkela, Fraga, Schaffner-Bielich, AV, Astrophys J. 789 (2014)

State-of-the-art EoS at all densities: interpolation between

- CET result for nuclear matter up to saturation density
- pQCD result for quark matter at high densities

Nontrivial insight: *Neutron star EoS constrained by pQCD limit*



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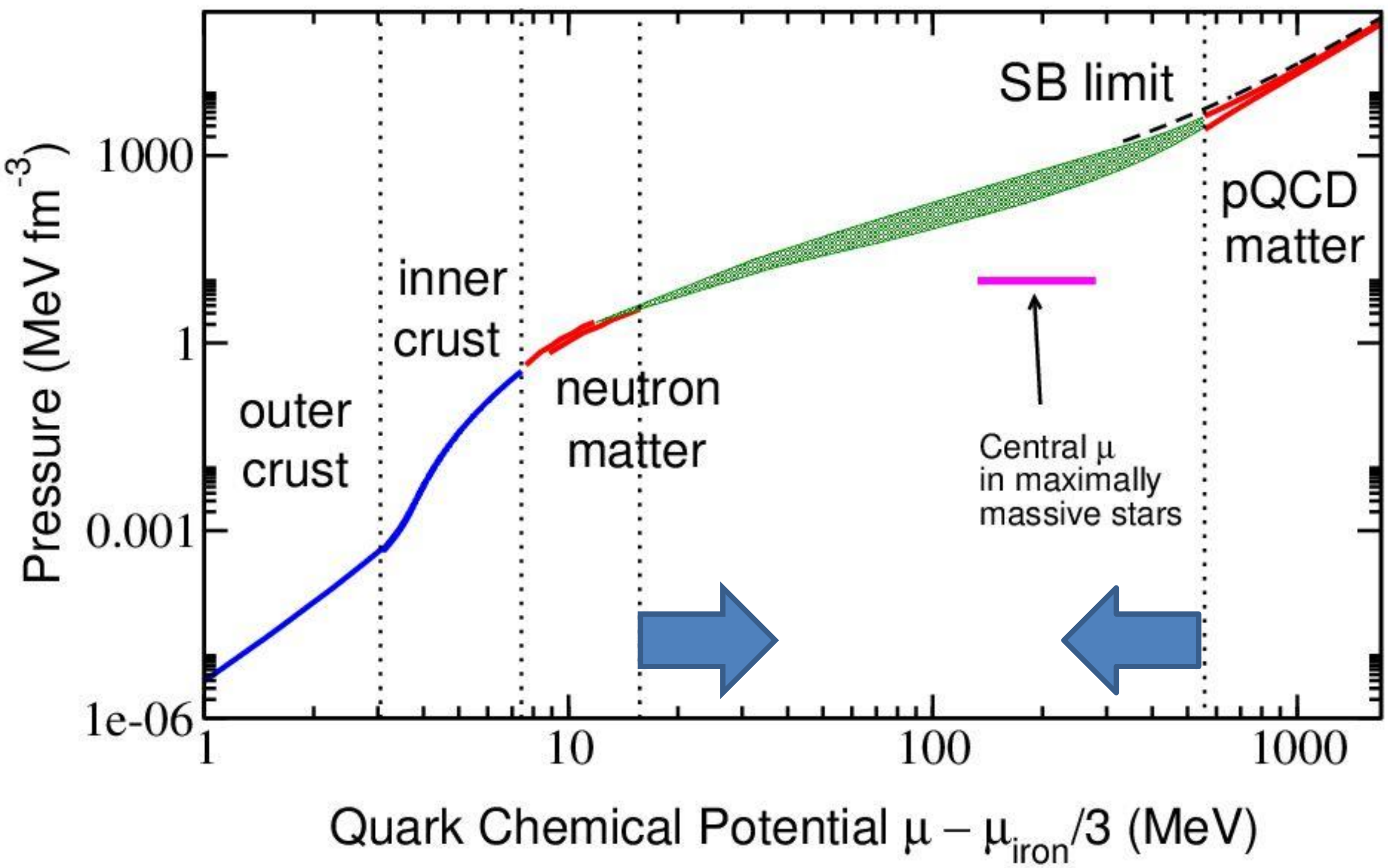

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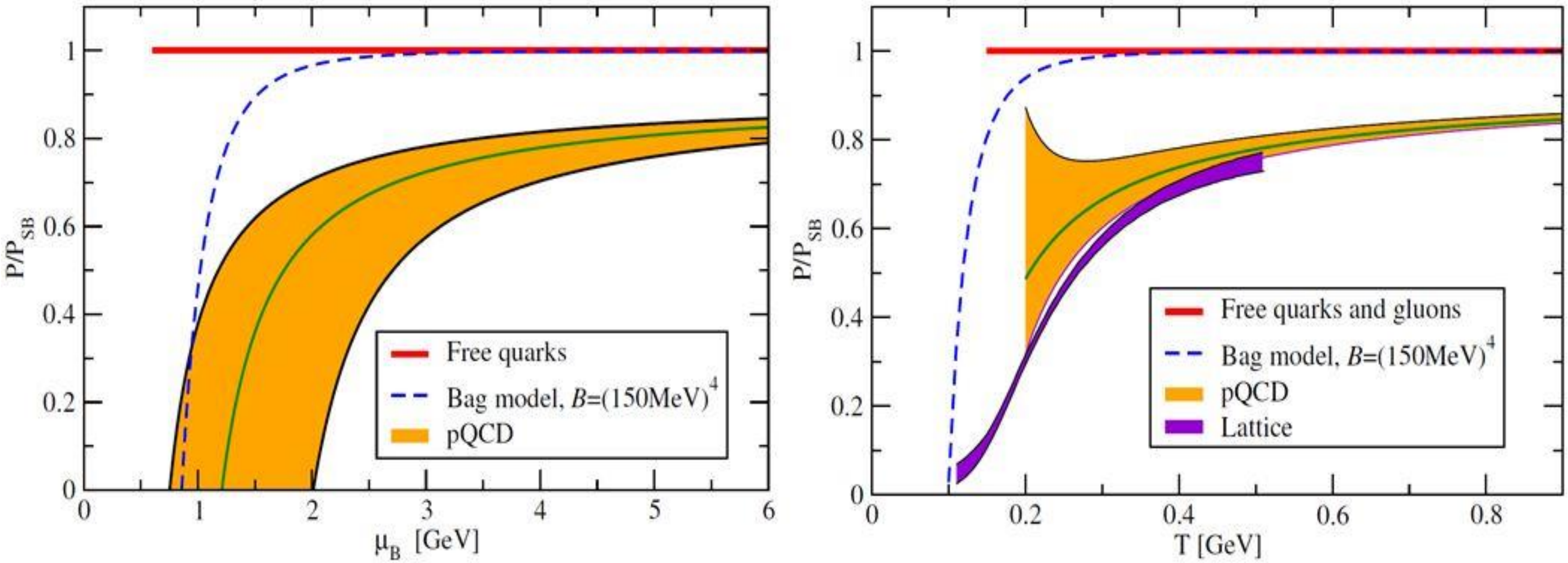

Cold quark matter EoS known to three-loop order, but convergence less than optimal. Therefore need to:

1) Work on extending weak coupling expansion to higher orders [Ghisoiu, Gorda, Kurkela, Romatschke, Säppi, AV]
2) Develop nonperturbative machinery for attacking dense quark matter at lower densities

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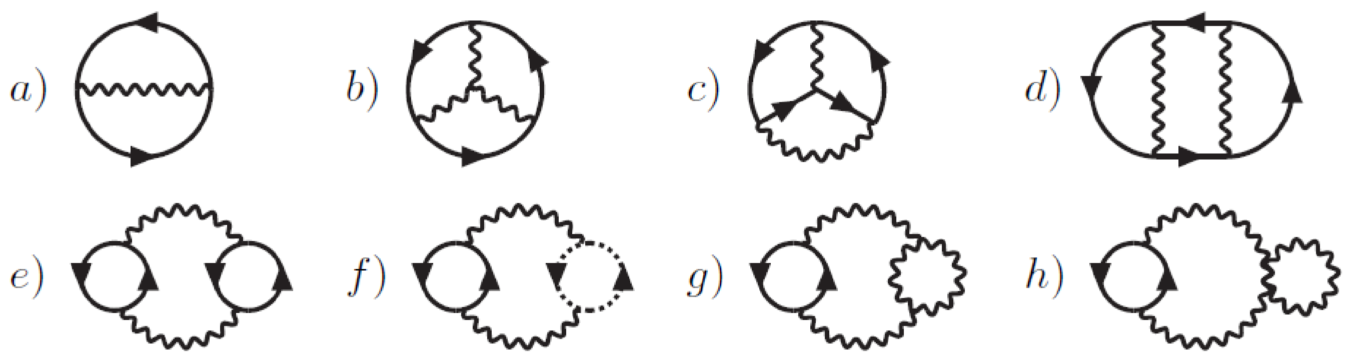
$$\Omega(T,\mu_u,\mu_d,\mu_s,m_s) = -T\log\int \mathcal{D}\bar{\psi}\mathcal{D}\psi\mathcal{D}A_\mu e^{-\int d^3x\int_0^{1/T}d\tau\mathcal{L}_{\rm QCD}},$$

$$\mathcal{L}_{\rm QCD} = \frac{1}{4}F^a_{\mu\nu}F^a_{\mu\nu}+\bar{\psi}_i(\gamma_\mu D_\mu+m_i-\mu_i\gamma_0)\psi_i$$

Perturbation theory: expansion of partition function in powers of gauge coupling *g* → Vacuum or bubble diagrams



$$p_n^{\rm bos} = 2\pi nT,$$
$$p_n^{\rm ferm} = (2n+1)\pi T - i\mu \qquad \int\frac{d^{4-2\epsilon}p}{(2\pi)^{4-2\epsilon}} \rightarrow T\sum_{p_n}\int\frac{d^{3-2\epsilon}p}{(2\pi)^{3-2\epsilon}}$$

$$\Omega(T, \mu_u, \mu_d, \mu_s, m_s) = -T \log \int \mathcal{D}\bar{\psi}\mathcal{D}\psi\mathcal{D}A_\mu e^{-\int d^3x \int_0^{1/T} d\tau \mathcal{L}_{\mathrm{QCD}}},$$

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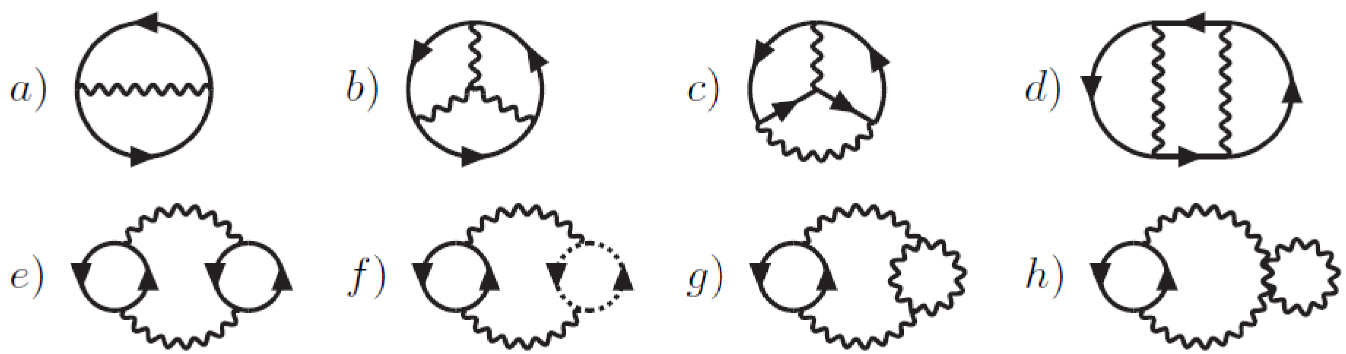
Problem in pQCD: infrared divergences at three-loop order from long-range (static) gauge fields



$$-\omega^2 + k^2 \rightarrow -\omega^2 + k^2 + \Pi(\omega, k)$$

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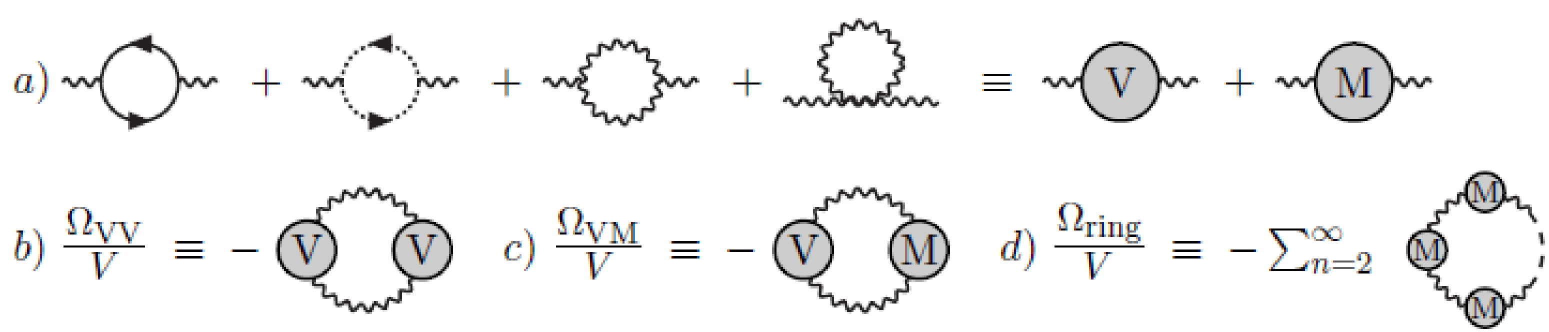
Solution: Resummation of IR sensitive contributions to the EoS: sum (certain) diagrams to infinite order or use EFT



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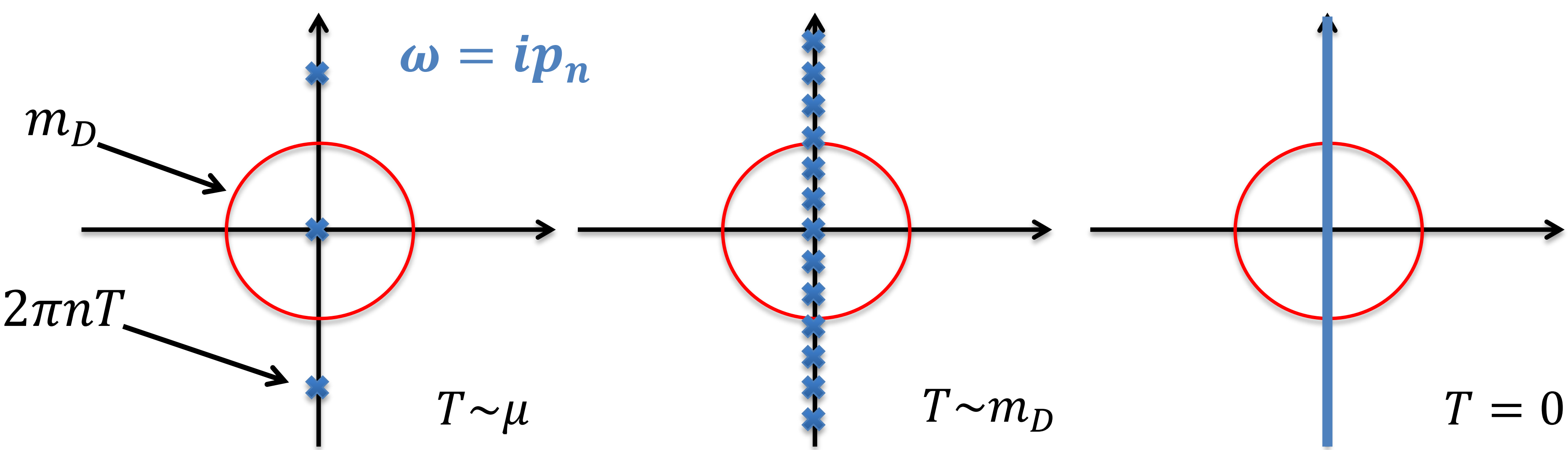

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$$p_{\rm QCD}^{\rm res} = p_{\rm QCD}^{\rm naive}+p_{\rm DR}^{\rm res}-p_{\rm DR}^{\rm naive}+p_{\rm HTL}^{\rm res}-p_{\rm HTL}^{\rm naive}$$

Effective theory for $n=0$ Matsubara mode. Necessary at $T\neq 0$; vanishes when $T\to 0$.

Effective description for $n\neq 0$ Matsubara modes with $k\leq m_D$. Dominates in the $T=0$ limit.

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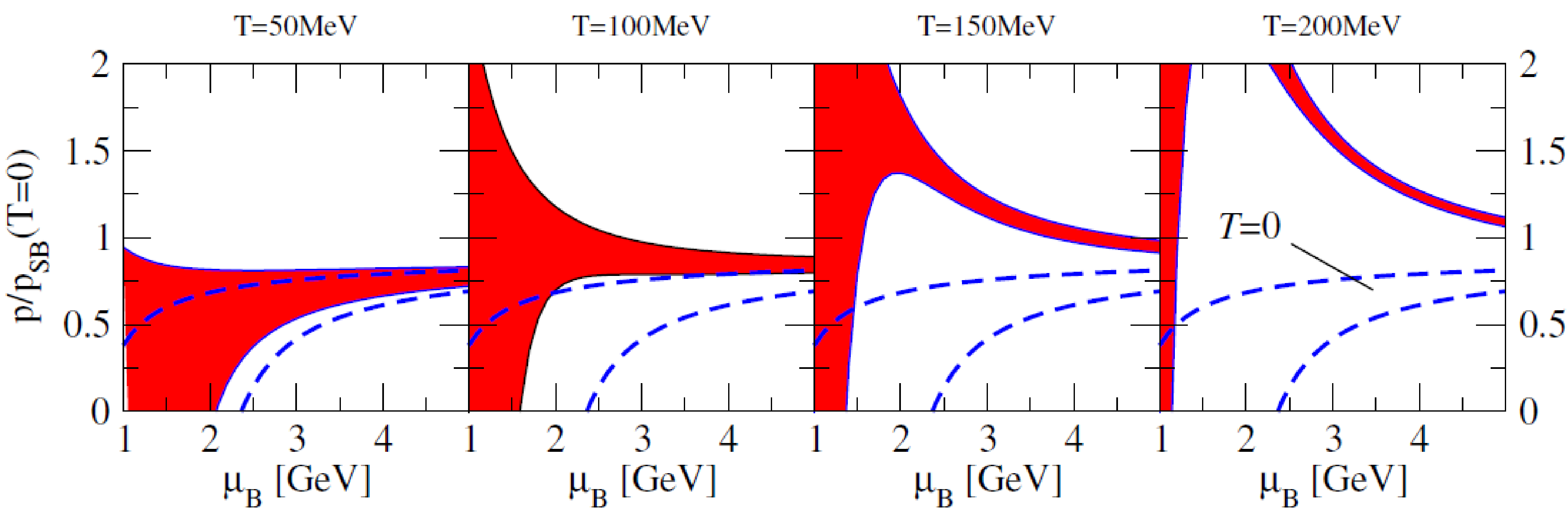
New: analytic result combining DR and HTL resummations → Small temperatures under control [Kurkela, AV, PRL 117, 042501]



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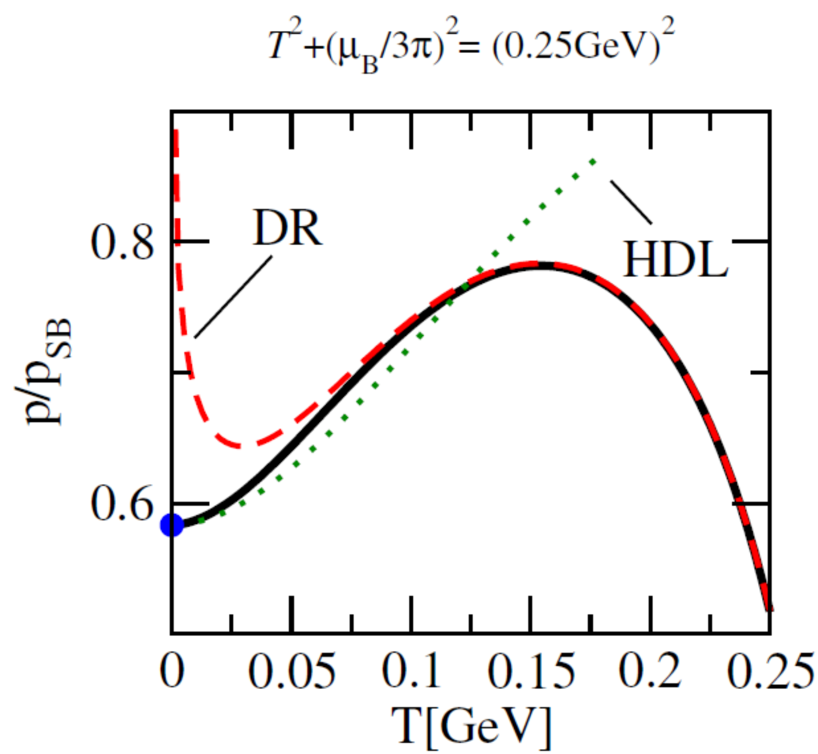

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- Analyticity: result trivially extendible outside beta equilibrium and charge neutrality
  - Leading finite-*T* correction: $O\left(T^2\ln\frac{T}{\mu_B}\right)$
- Practical uses in neutron star merger calculations: need finite temperature corrections on a large density interval
  - Plan: Constrain low-density EoSs with new result

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Holography a very successful tool in heavy ion physics.
However, in cold and dense QCD:

- Need (finite density of) fundamental flavors, while $N = 4$ SYM only contains adjoint fields
- $N_c = 3$ very important: baryon structure, color superconductivity, ...
- Need to break SUSY and conformality & impose confinement

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Introduce N_f D7-branes to geometry – corresponds to introduction of N_f fundamental $\mathcal{N}=2$ hypermultiplets to gauge theory

- Theory possesses global $U(N_f) \sim SU(N_f) \times U(1)$ symmetry, identifiable with baryon symmetry $U(1)_B$
- Finite density: turn on gauge field in D-brane worldvolume
- Probe limit $N_f \ll N_c$: classical SUGRA with no backreaction

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Extrapolate to three colors in quark matter phase:

- D3-D7 always in deconfined phase: apply setup only for description of quark matter
- Ignoring quark pairing, large-N_c limit not necessarily a bad approximation for deconfined matter – works nicely at high T, with highly suppressed corrections

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Controlled breaking of symmetries possible in top-down models, but getting close to QCD tough

- Relevant bottom-up models: Sakai-Sugimoto, VQCD,...
- Bonus: ultimately may be able to describe also the nuclear matter phase

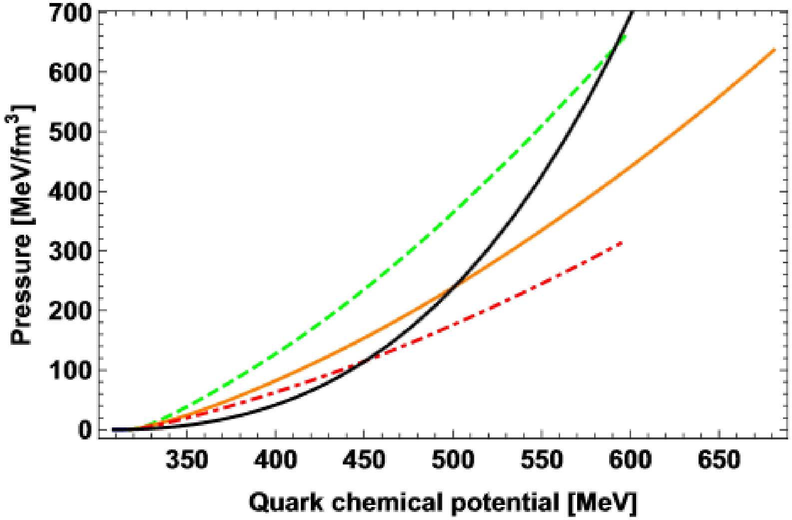
Here: EoS of strongly coupled quark matter with $N_c = N_f = 3$, at $T = 0$ [Hoyos, Jokela, Rodriquez, AV, PRL 117, 032501]:

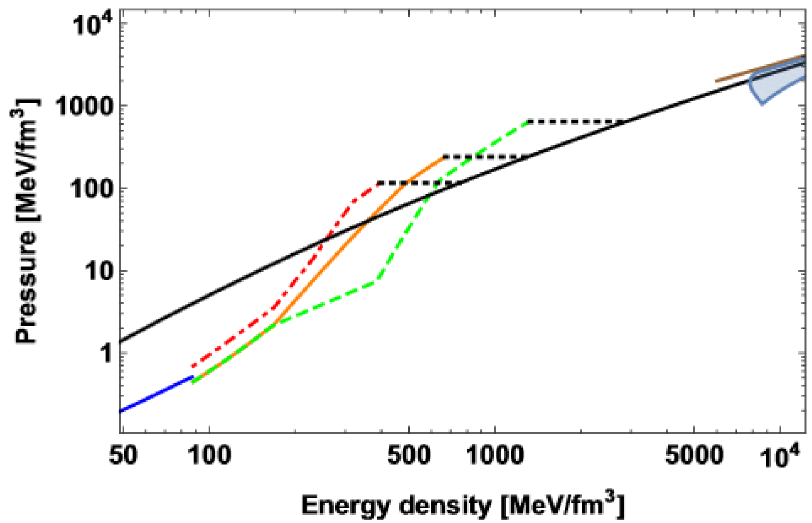
309 MeV from $p(\mu_B) = 0$

$$\varepsilon = 3p + m^2 \sqrt{\frac{N_c N_f}{\underbrace{4\gamma^3 \lambda_{YM}}_{3\pi^2}} p} = 3p + \frac{\sqrt{3} m^2}{2\pi} \sqrt{p}$$

from correct UV limit

Matching to state-of-the-art nuclear matter EoSs from CET:





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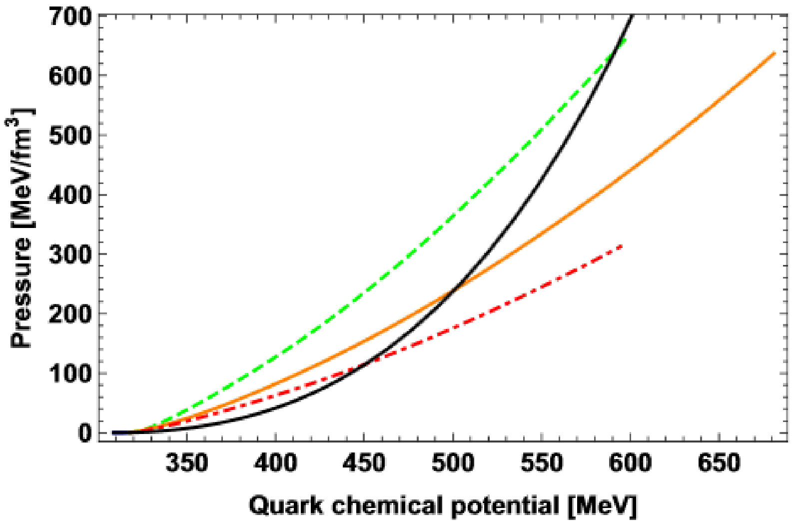
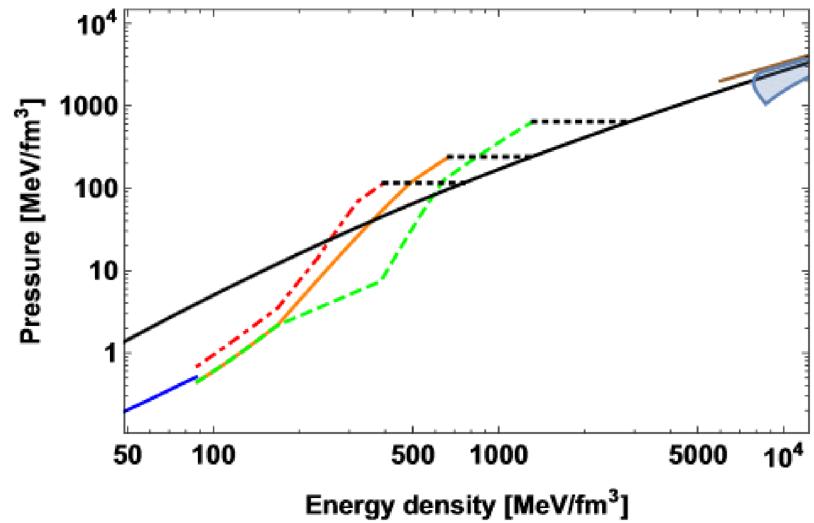
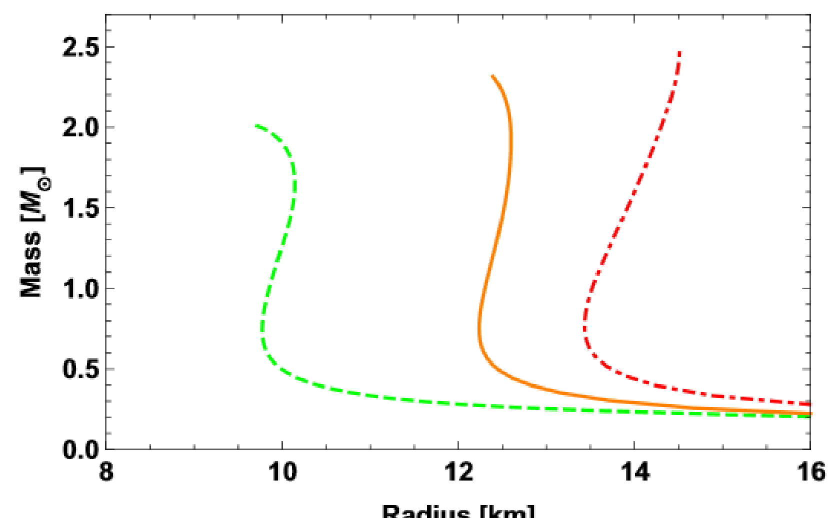




Predictions:

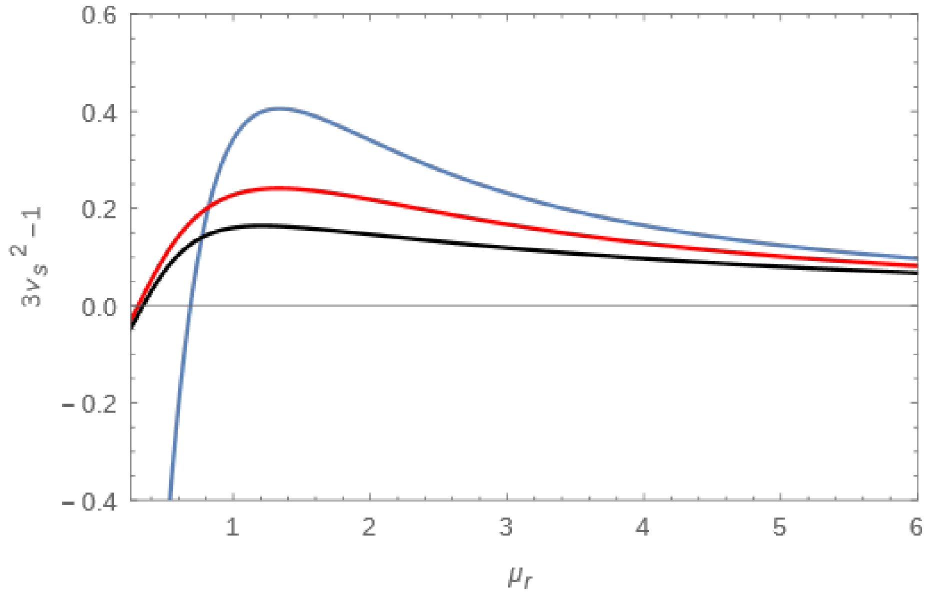
- Strong 1st order transitions at phenomenologically reasonable densities: 2.4-6.9n_s
- No quark matter inside stars (stars become unstable at transition)

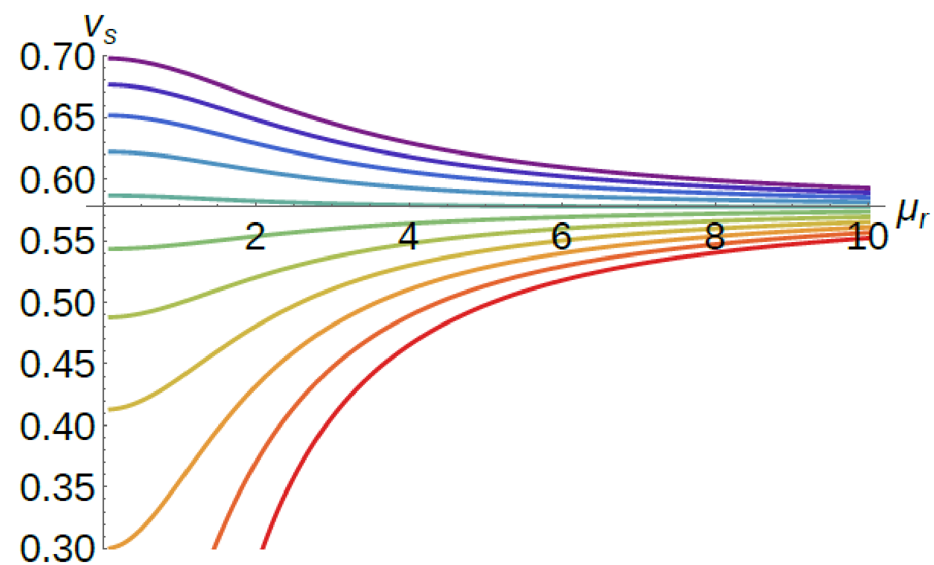


Strength of the transition due to softness of holographic EoS: $c_s^2 = 1/3$ in conformal theories

New result: demonstration that asymptotically AdS models – i.e. field theories with UV fixed points – can produce $c_s^2 > 1/3$ [Hoyos, Jokela, Rodriguez, AV, PRD 94, 106008]

Ultimate hope: understanding universal properties of strongly coupled quark matter





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1. Identifying the properties – and identity – of neutron star matter from 1st principles is hard…
2. …but not impossible if we use all available tools from low to high density
3. Important recent progress in understanding IR sector of cold and dense QCD: $T \neq 0$ effects now under control
4. Top-down holography may provide valuable insights into strongly coupled quark matter